"High Angular Resolution and Position Determinations
by Infrared Interferometry"

A fairly complete "stellar" interferometer system was installed on the two 30 inch auxiliary mass telescopes at Kitt Peak National Observatory during late 1973. A series of tests were carried out to determine the signal-to-noise obtained on various astronomical objects, to fix the parameters of the baseline, to perfect the control of the telescopes, to adapt some of the input controls and the output information of the system for appropriate use on computers available at Kitt Peak. The first attempt to obtain interference fringes from an astronomical object, the planet Mercury, was carried out in the Spring of 1974. This test was not successful for reasons which are not entirely clear, but perhaps because (1) the performance of the interferometer was impaired substantially by two imperfect mirrors which had been installed in the optical path and which produced astigmatism and (2) fluctuations within the long optical paths of the two auxiliary McMath telescopes were fairly severe. All major parameters of the system were subsequently individually tested, the faulty mirrors replaced, and interference fringes obtained from a local source of 10 micron radiation installed in a position which would illuminate both telescopes. The subsequent test of the interferometer on Mercury in August, 1974 was highly successful. The results are described in some detail in the accompanying preprint which has been submitted to The Physical Review Letters for publication.

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1. "Distance Meter Helps Track the Stars", A. L. Betz, Hewlett-Packard Civil Engineering Products (House Organ) INSIGHT, Vol. 1, No. 4, pp. 1-3, August, 1973.

2. "Berkeley Heterodyne Interferometer", A. L. Betz, Workshop on Coherent Detection in Astronomy, Rhenen, The Netherlands, April, 1974, Utrecht Astronomical Institute, to be published in the Conference Proceedings.

3. "Infrared Heterodyne Spectroscopy of CO_2 on Mars", D. W. Peterson, M. A. Johnson, and A. L. Betz, NATURE, Vol. 250, No. 5462, pp. 128-30 (1974).

4. "A 10μm Heterodyne Stellar Interferometer", M. A. Johnson, A. L. Betz, and C. H. Townes, submitted to Physical Review Letters, October, 1974.

Reports at Scientific Meetings

"An Infrared Stellar Interferometer Using Heterodyne Detection", M. A. Johnson, 1972 Annual Meeting, Optical Society of America, October, 1972.

"Heterodyne Spectroscopy of CO_2 on Mars", D. W. Peterson and M. A. Johnson, 142nd meeting AAS, March, 1974, Lincoln, Nebraska.

"Results from the 5.5 Meter Infrared Stellar Interferometer", M. A. Johnson, A. L. Betz, and C. H. Townes, AAS Gainesville meeting, December, 1974.

DISTANCE METER HELPS TRACK THE STARS

by Al Betz
University of California

Recent progress in quantum electronics has extended the advantages of coherent signal detection techniques from the microwave region up through the infrared and visible portions of the electromagnetic spectrum. A new type of instrument, capable of high angular resolution, made possible by these technological advances is the infrared heterodyne interferometer constructed by Michael Johnson, Daniel Galehouse, and Albert Betz, under the direction of Charles Townes of the Physics Department of the University of California, Berkeley. A prototype interferometer has been installed at the McMath Solar Telescope at Kitt Peak National Observatory near Tuscon, in order to demonstrate the feasibility of heterodyne techniques in the determination of stellar sizes and shapes. Basically, the instrument expands upon previously developed techniques in radio astronomy, whereby if one is able to measure the degree of coherence between two points along the same wavefront emitted by a distant source, and make this measurement as a function of the separation between these two points, then the spatial source brightness distribution can be determined. In other words, by measuring the coherence between stellar signals from sufficently separated receivers, one can resolve the diameters of distant stars.

In Figure 1 we see a representation of the basic situation. Points A and B correspond to positions along the same wavefront emitted by the star. We wish to measure the degree of coherence between starlight at A and at B. In this figure, the wavefront is first received by the east telescope; later, at a time difference corresponding to the light travel time between points B and C, the same wavefront is received in the west telescope. No long-term temporal coherence is assumed for the starlight, hence to obtain any measure of spatial coherence of the light, one must compare signals from the same wavefront. Obviously, some means must be contrived to effectively delay the east signal until the appropriate wavefront is detected at the west. The straight forward approach would demand introducing an optical delay length above the east telescope, a formidable task when one considers that the accuracy required is proportional to the signal bandwidth accepted, and that even for only a 10% bandwidth centered at 10 micron wavelength, the stability and accuracy required for the optical delay would exceed 100 μ.

In the Berkeley interferometer, the infrared starlight from each telescope is mixed in a high speed photodetector with a stable 100mw CO_2 laser local oscillator beam. The photodetector, in this case a highly doped CuGe

photocondutceive crystal, responds as a square law device fast enough to allow an intermediate frequency bandwidth beyo. d 1 GHz. So, that part of the stellar signal within 1 GHz of the CO_2 laser frequency of 30,000 GHz (10μ) is converted down to radio frequencies. The process of linear in the sense that all the phase and amplitude information of the original starlight signal is preserved (Figure 2). Now the correct delay may be introduced into the east signal path through an appropriate adjustible length of coaxial cable. The tolerence on cable length accuracy is relaxed to an amount proportional to a 1 GHz bandwidth, on the order of a few cm. The price paid for this convenience is a greatly reduced signal bandwidth and hence a reduction in system signal-to-noise ratio, yet enough signal remains to permit a good interference measurement in the order of a few minutes. As shown in Figure 2, the appropriately amplified and delayed IF signals are passed into a broadband multiplier, or correlator, and subsequently processed for maximum coherence information.

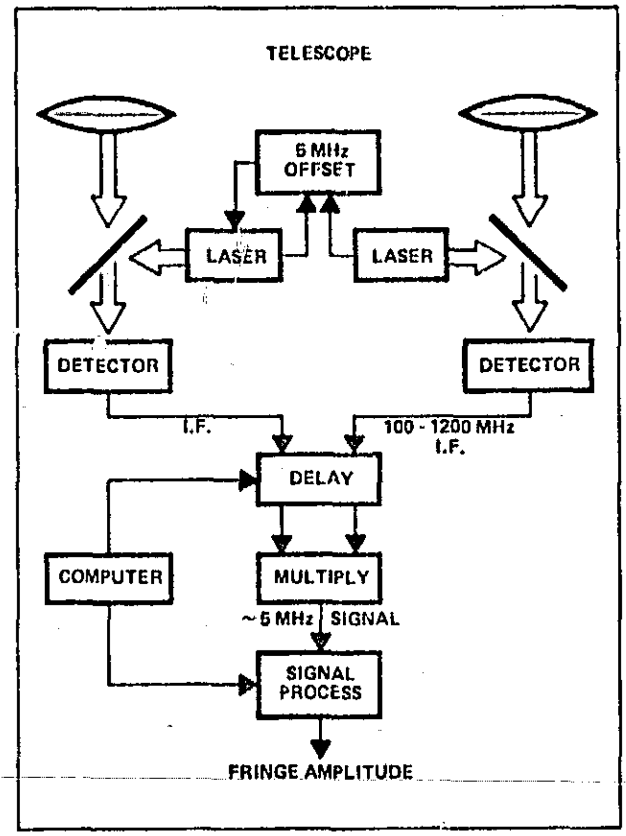

Figure 2

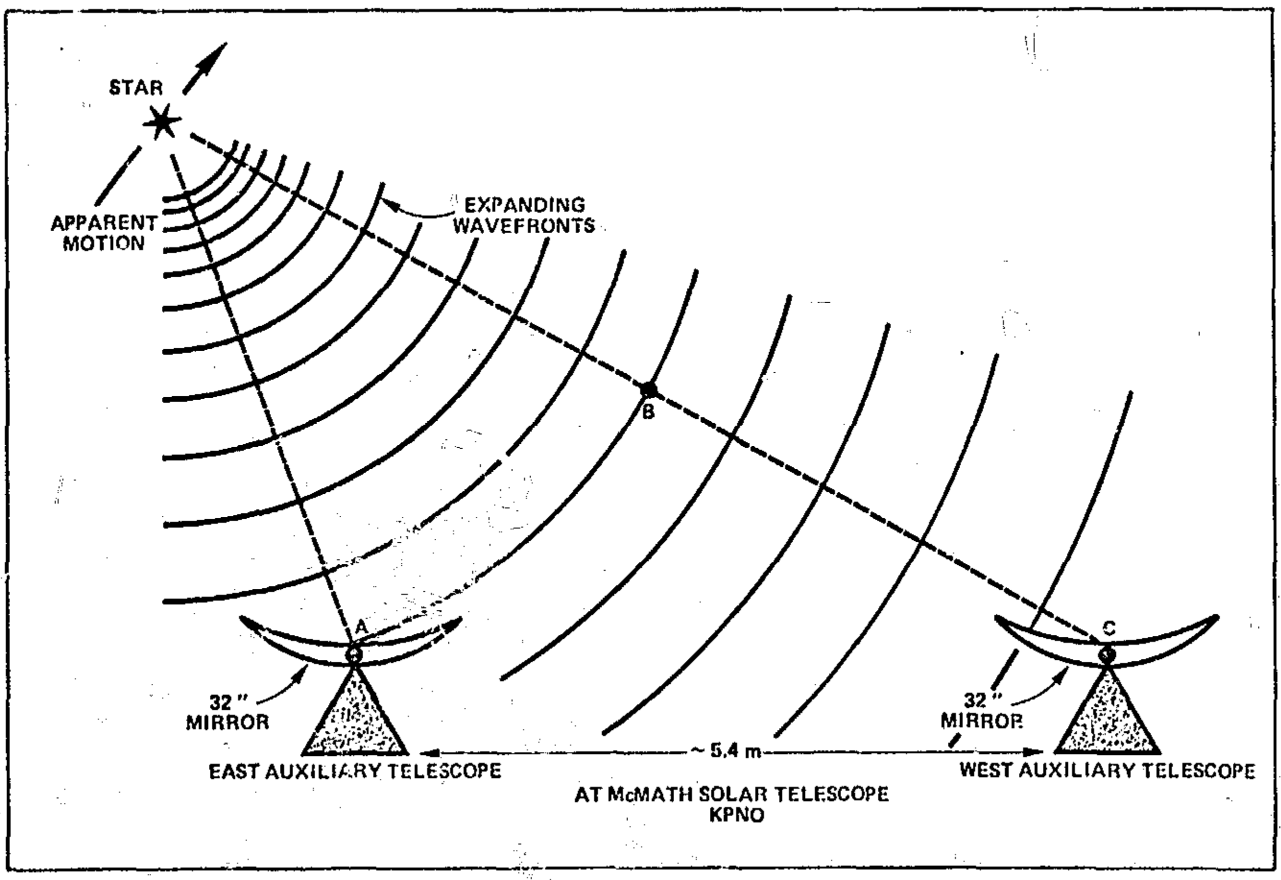

Figure 1

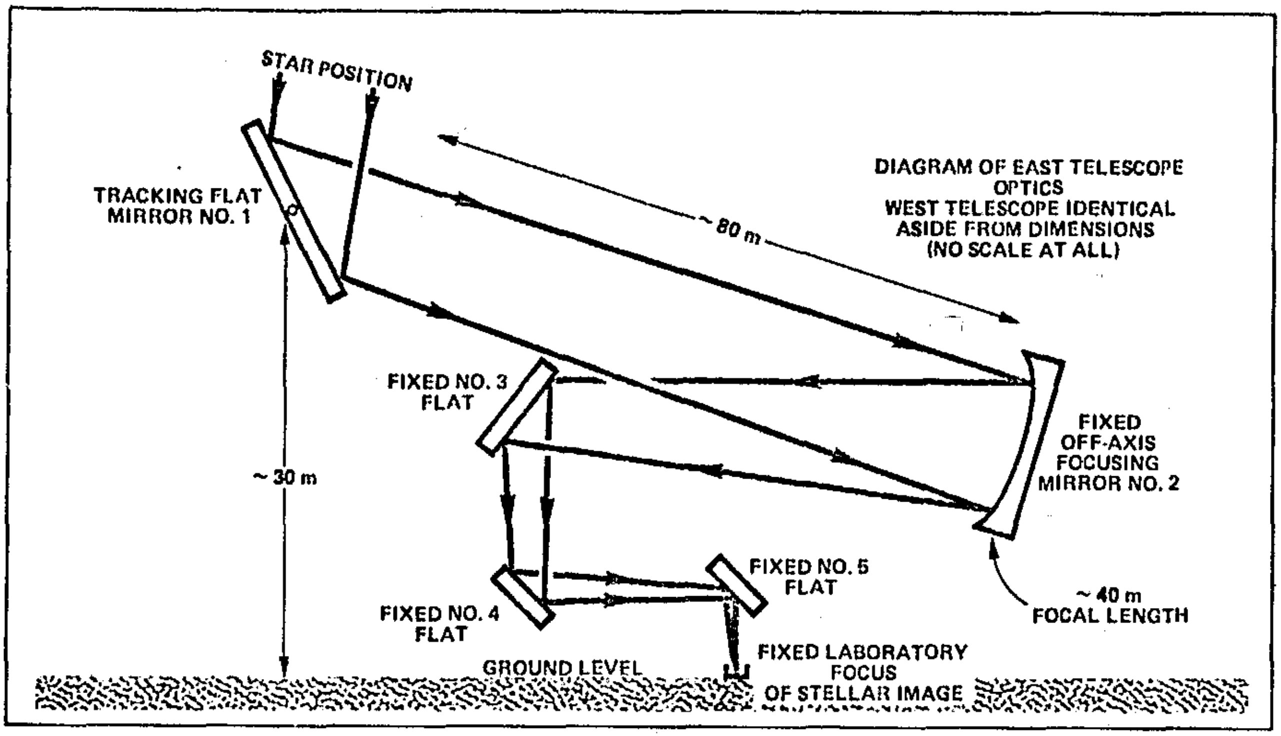

Figure 3

In the construction and alignment of the instrument, one of the most difficult calibration measurements was thought to be that of determining the optical path length difference through the two telescopes. The two auxiliary solar telescopes are not identical; in fact, the optics are not simple paraboloids as detected in Figures 1 and 2, but actually consist of a series of flat and focusing mirrors that transmit the infrared signals from a receiving tower to a more convenient observing station near ground level (Figure 3). In this way, the stellar image remains fixed down in a laboratory environment, while the stars apparent motion is tracked across the sky. It is important to know the relative optical path length difference between the mirror sets of the two telescopes, in order to properly compensate the electrical delay length for I.F. signals; and this path length difference must be determined to an absolute accuracy in the neighborhood of one centimeter. The constraints of the measurement are such that the mirror surfaces are rather inaccessible for conventional measurement, the distance is long for the accuracy desired, and the optical surfaces may be neither touched nor disturbed. A simple solution for this otherwise difficult problem was found to be the Hewlett-Packard Model 3800B Distance Meter. The No. 1 mirror (Figure 3) was aligned perpendicular to the optic axis of one telescope; the Distance Meter was directed at the multi-reflected image of the No. 1 mirror surface, and the optical path length read from the instrument's dials. Similar sightings through the optics of the other telescope completed the entire operation. The strength of the return ranging signals allowed an experimental repeatability of better than 2mm in the sightings over a total path length exceeding 120 meters.

Now that the initial calibration of the interferometer has been completed, observations of bright infrared stars will determine the stability of the coherence signal in the presence of path length variations caused by atmospheric turbulence. The measurement is of prime importance in determining feasible future telescope separations of more ambitious proportions. At present, the separation, or baseline, is slightly more than five meters, and at a 10μ wavelength only allows the angular resolution of astronomical objects larger than approximately ½ arc sec. After these initial tests, the baseline will be expanded into the region of 50 to 100 meters or more, at which point the angular size of many infrared stellar objects will be determinable. □

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Session: Interferometry

Contributor: Albert Betz, Department of Physics, University of California, Berkeley

Summary of Contribution:

BERKELEY HETERODYNE INTERFEROMETER

The major effort of the infrared heterodyne program at Berkeley has been the design and construction of a prototype heterodyne stellar interferometer, in order to demonstrate the feasibility of heterodyne techniques in measuring angular diameters of bright infrared stars and dustshells. Since November 1972, the instrument has been installed at the McMath Solar Telescope of Kitt Peak National Observatory near Tucson, Arizona. Alongside the main 60 inch solar telscope, there exist two separate auxiliary solar telescopes suitable for use together as a stellar interferometer. Each auxiliary telescope consists of a steerable flat heliostat of 0.4 m^2 collecting area followed by a fixed off axis focussing mirror and subsequent optical flats, which direct the beam to a fixed focus location in the observing room. (Fig. 1) The steerable flats of these two separate telescope are situated on a direct east-west baseline with a center to center separation of 5.5 meters. At the fixed focus of each telescope, an infrared heterodyne receiver is positioned to receive the incoming

radiation. (Fig. 2) Each receiver consists of a high speed Cu:Ge photomixer cooled to 4 Kelvin and a stable one watt sealed CO_2 laser operating near 11 μm as the local oscillator.

The intermediate frequency signals from each photomixer are amplified within a bandwidth of 1200 MHz, and then directed to a balanced coaxial cable delay line which compensates for the changes in optical path length produced as the infrared source is tracked across the sky. The 1200 MHz bandwidth of these I.F. signals dictates that this cable delay always be maintained accurate to a few centimeters. The relative phase between the two photomixer I.F. signals is defined by phase-locking the two CO_2 lasers together, with a fixed frequency offset of approximately 5 MHz between them. This frequency offset between the lasers is introduced for purposes of convenience in the subsequent signal correlation and processing and is not fundamentally required for the experiment. However, the actual value of the offset is necessitated by undersirable frequency pulling effects between the lasers at offsets below 100 KHz. Following the electronic delay line is a broadband radio frequency correlator which multiplies together the two appropriately delayed and amplified photomixer signals. The output signal from the RF correlator is then demodulated with the 5 MHz offset between the laser oscillators and the subsequent demodulated signal is then electronically analyzed in a

manner optimized to yield the desired information on the fringe amplitude. With the operational wavelength of 11 μm and a baseline separation of 5.5m, the resulting fringe spacing for the interferometer is 0.4 arcsec at zenith. This angular resolution by itself is not considered sufficient to adequately resolve the angular diameter of any known bright infrared sources, with one possible exception. However, this fringe spacing seems quite suitable for verifying the capabilities of a prototype heterodyne interferometer before eventually expanding the baseline to more useful and ambitious dimensions.

The first system tests were performed in December 1972 and consisted of measuring the detection sensitivity of each of the two telescope-receiver combinations. The detector performances on stellar and planetary sources agreed well with calculations based upon laboratory calibrations on a blackbody source, and yielded typical signal to noise ratios after a one second period of integration of: 20 on Mercury, 11 on the Moon, 2.5 for Mars, 1.5 on Venus, 0.3 on VY Canis Majoris, and 0.15 on α - Orionis. These values all assume operation with a 0.4 m^2 area solar telescope with a transmission at 11 μm of .85, and the laser local oscillator operating on the transitions of $^{13}C^{16}O_2$. By setting the steering flat of each solar telescope to an autocollimation position, the telescope transmission can be measured directly at the wavelength of interest. Also, the

atmospheric transmission is determined by measuring the heterdyne signals from the Moon or Mars as a function of zenith angle. Averaged over the band of 100 to 1200 MHz, the zenith transmission on the P(20) line of $^{12}C^{16}O_2$ at 10.57 μm was .45 ± .05; transmission of the $^{13}C^{16}O_2$ lines near 11.2 μm was .90 ± .05. Recent advances in detector technology now permit nearly an order of magnitude improvement in detector sensitivity over the values quoted above to sensitives now only a few times worse than the quantum noise limit. As our present stellar signal levels were regarded as insufficient for a precise alignment and test of the interferometer system, it was decided to use the planet Mercury as an overresolved calibration source. When Mercury is near maximum apparent elongation from the sun, the subsolar point lies on the planet's edge, producing a rather strong temperature gradient across the surface of the planet as viewed from the Earth. Even though the angular diameter of Mercury exceeds by an order of magnitude the zenith fringe spacing of our interferometer, when the planet's temperature distribution is convolved with the antenna pattern of the interferometer, the net fringe modulation signal is found to be significant. For our system sensitivity, the net fringe signal to noise ratio on Mercury is calculated to be approximately 1.5 to 1 with the planet in transit, 3 to 1 with Mercury at ± 4 Hrs. Hour Angle, and 8 to 1 with the planet at ± 5 Hrs. Hour Angle.

This rapid increase in signal to noise ratio with increasing hour angle is the result of a broadened fringe spacing with shortened apparent baseline at these hour angle positions. A test, however, of the entire interferometer system on Mercury at its greatest western elongation this past March failed to produce any fringe signal whatsoever. Since a laboratory test of the interferometer with a blackbody source near the heterodyne receivers had been successful in producing a fringe coherence signal, it was felt that optical air turbulence within the structure of the solar telescope was possibly destroying the phase coherence of the fringe signals. The optical path length within the solar telescope from each steering mirror to its respective fixed focus is approximately 120 meters. At present, additional tests are being conducted to determine the magnitude and source of any air turbulence within the telescope structure that might destroy the relative coherence between the two separate optical paths. If these studies indicate the disturbances are significant, then an optical network will be installed within the telescope structure to monitor and compensate for these phase fluctuations produced by the air turbulence. Basically, the network is built around another stable CO_2 laser used only as a reference oscillator. The output of this third reference laser is divided and each half propagated down the optical path of one auxiliary telescope, starting at the steering flat and

down to the fixed focus 120 meters distant. In the observing room, each local oscillator laser is then phaselocked to that half of the reference laser beam associated with its respective telescope. In this way, each L.O. laser would effectively track out the phase perturbations produced by air turbulence along the path of its telescope beam. It is anticipated that these tests could be concluded within the next few months.

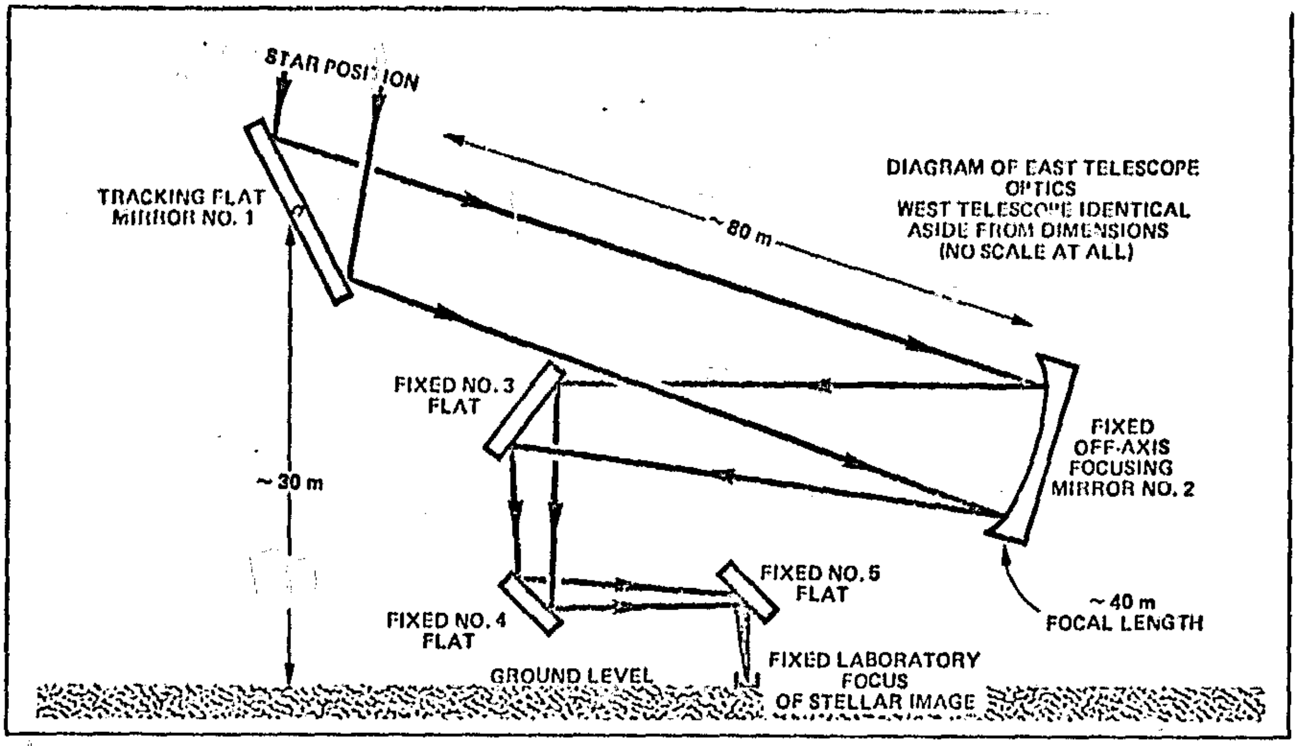

FIGURE 1.

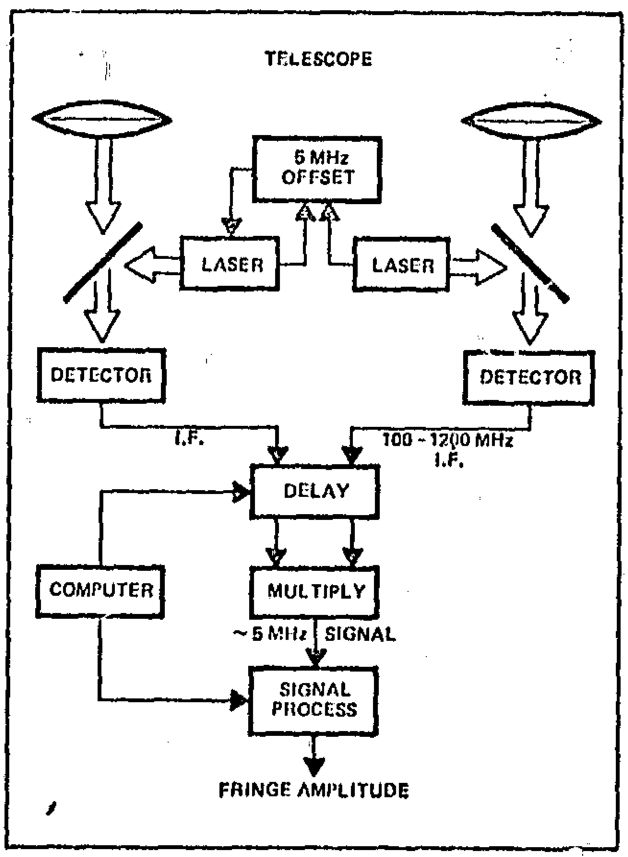

FIGURE 2

(Reprinted from Nature, Vol. 250, No. 5462, pp. 128–130, July 12, 1974)

Infrared heterodyne spectroscopy of CO_2 on Mars

THERE has been considerable interest in applying infrared heterodyne techniques to astronomical problems[1-3]. We have used an infrared heterodyne spectrometer operating near 11 μm with a resolving power of 1.5×10^6 to obtain spectral line profiles of carbon dioxide absorption in the Martian atmosphere. The multichannel system determined shapes of three lines in the 10^0 0–00^0 1 vibration-rotation band of $^{13}C^{16}O_2$ and found equivalent widths about 50 MHz (0.0017 cm^{-1}). A lower limit of 670 MHz (0.022 cm^{-1}) on the equivalent width of the P(20) line of $^{12}C^{16}O_2$ was also obtained.

Figure 1 shows a block diagram of the equipment. Two concave mirrors not shown in Fig. 1 matched the diameter and wavefront curvature of the laser and telescope beams at the combining beam splitter. The 9% of the laser beam which was reflected by the beam splitter and the 91% of the telescopic beam which was transmitted were focused on to a copper-doped germanium photomixer cooled to 4 K. The photomixer signals were amplified over a frequency band from 100 to 1,500 MHz and fed into a radiofrequency mixer with a variable local oscillator frequency. The output of the mixer was fed into a filter bank which simultaneously measured the power in eight channels, each 18 MHz wide, equally spaced from d.c. to 150 MHz. Each channel had a synchronous detector locked to the chopping frequency and followed by a low pass filter. The eight outputs of the filter bank were sampled and digitised by computer. To cancel effects between the two parts of the sky seen by the dual beam chopper, the planet was periodically alternated from one beam to the other.

As a periodic calibration of the system sensitivity, a black body at 500 K was placed in front of the chopper. By placing the heliostat in autocollimation, the telescope transmission was found to be 0.85. Atmospheric transmission was determined by measuring heterodyne signals from the Moon and Mars as a function of zenith angle. Averaged over the band of 100 to 1,000 MHz, the zenith transmission on the P(20) line of $^{12}CO_2$ (wavelength 10.57 μm) was 0.45, lower than may be expected from previous measurements[4], and transmission of the $^{13}CO_2$ lines near 11.2 μm was 0.90. The approximate standard deviation in each case was 0.05. The contribution of water vapour to the absorption was estimated to be 0.05 to 0.10 (ref. 5). The system sensitivity for each 18 MHz channel was thus calculated to be 5×10^{-22} Wm^{-2} Hz^{-1} at the top of the Earth's atmosphere, assuming operation on a $^{13}CO_2$ line, radiation of one polarisation, and a signal to noise ratio of unity for one second of integration. Because of the antenna properties of the heterodyne receiver[6] and the shape of the heliostat mirror, the system was only sensitive to radiation in an elliptical beam measuring 4 arc s in declination (dec) and 3 arc s in right ascension (RA). The angular diameter of Mars was about 14 arc s at the time of observation.

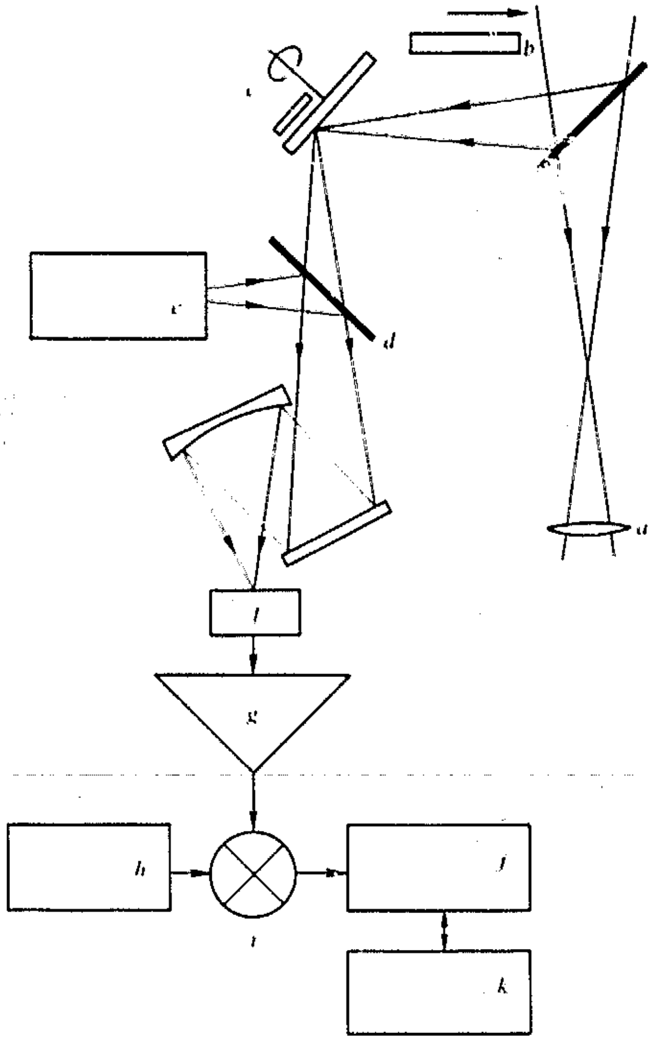

Fig. 1 Block diagram of the equipment located at the auxiliary solar telescope, located near the focal plane. *a*, Guiding eyepiece; *b*, black body; *c*, chopper; *d*, beamsplitter; *e*, CO_2 laser; *f*, germanium: copper photomixer; *g*, amplifier; *h*, radiofrequency local oscillator; *i*, radiofrequency mixer; *j*, eight channel filter bank; *k*, computer. The telescope consists of a steerable flat heliostat with a collecting area of about 0.4 m^2, followed by a fixed off-axis focusing mirror and three flat mirrors which direct the beam to the equipment. A rotating mirror in the focal plane of the telescope chopped the source against a sky background at 150 Hz. A linearly polarised laser used as an infrared local oscillator was operated in the TEM_{00} mode, and stabilised on various rotational transitions of the 10^0 0–00^0 1 band of CO_2

In order to understand how the spectral information was obtained it is necessary to consider how the spectrum was folded on itself in the two mixing operations (Fig. 2). The continuum infrared radiation is folded over into the absorption profile and decreases the fractional depth by a factor of two. We assumed that the absorption lines were symmetric and tuned our radio frequency local oscillator to the expected centre of the absorption line. This frequency was calculated from the relative velocities and rotation rates of Earth and Mars, and typically had a value near 1,100 MHz. The output of the radio frequency mixer thus represents the amplifier output power folded about the frequency at line centre of the radio frequency local oscillator. This is quite accurate for the $^{13}CO_2$ lines because their widths are considerably less than both the velocity shift and the width of the entire filter bank. The $^{12}CO_2$ line, however, is very broad and its interpretation is more difficult.

In a computer simulation of the Martian atmosphere we assumed an atmosphere of 100% carbon dioxide consisting of plane-parallel layers of constant temperature and pressure (Fig. 3). The rate of change of temperature with altitude is conventionally defined as the lapse rate, and the height at which the pressure drops by a factor of e is similarly defined as the scale height. We assumed a constant lapse rate and a scale height, at the surface, of 11 km. Parameters used in the simulation were:

T_s=surface temperature (given separately for each line in Fig. 3);

$\Delta T_{AS}=T_s$ minus the temperature of the atmosphere at the surface;

Γ=temperature lapse rate (degrees km^{-1});

P_s=surface pressure (mbar).

In addition we defined the parameter

$z=[P_s/6 \text{ mbar}]\cdot R(13/12)\cdot A(13/12)$.

This is proportional to the number of $^{13}CO_2$ molecules in the atmosphere and to the transition rate, where

$R(13/12)$=ratio of isotopic species by number and $A(13/12)$=ratio of Einstein A coefficients for equivalent lines in the two isotopic species.

The best values of Γ, ΔT_{AS}, and z each depend to a large extent on which values are taken for the other two parameters (Table 1). This is because the number of absorbing molecules and their average temperature must remain nearly fixed in order to maintain the same absorption profile for each model. Four sets of these parameters which give equally good fits to the data are given in Table 1. Model 1 (Table 1) uses the adiabatic lapse rate for Mars.

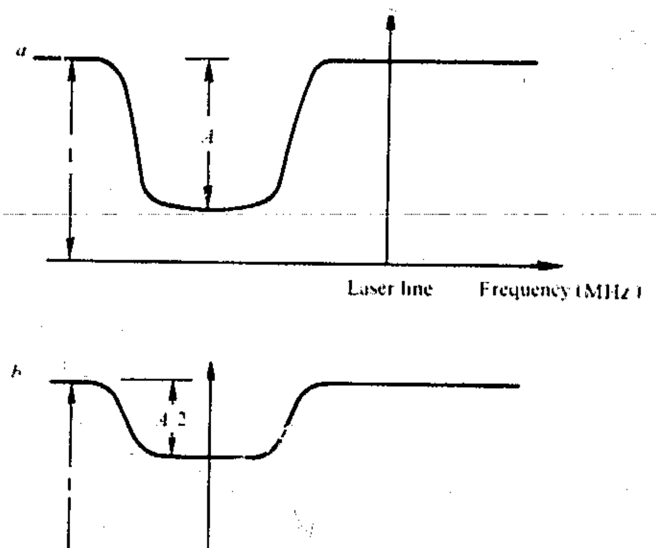

Fig. 2 Folding of the absorption line because of mixing: *a*, schematic representation of a Martian infrared absorption line shifted in frequency from a laser line of the same molecular transition by the relative motion of Earth and Mars. *A* is the fractional depth of the absorption. Infrared frequencies equally spaced on either side of the laser line appear at the same place in the radiofrequency spectrum of the amplifier output. *b*, the absorption line as it appears at the amplifier; *c*, the absorption line as it appears at the mixer output. The numbers along the abscissa represent the eight channels of the filter bank into which the mixer output is fed.

Higher lapse rates would be quickly reduced to the adiabatic case by convection. Model 4, with zero lapse rate, is physically unrealistic but is included to show that z does not continue to decrease as the lapse rate further decreases. The results themselves do not put upper bounds on ΔT_{AS} and z; values for z which fit the data are, however, in all cases larger than expected and values of ΔT_{AS} were therefore chosen so as to minimise z.

Statistical errors in the data produce uncertainties in the model. The standard deviation of T_s is about 1.5 K for the P(16) line and about 3.0 K for P(22) and P(26); systematic errors in the calibration cannot, however, be completely ruled out. The value of T_s is obtained from the black body calibration. Based on this calibration our measurement of the lunar flux is about 15% higher than the published value and has a standard deviation of 3% but the discrepancy is, at least in part, because of imprecise knowledge of the Sun angle at the point observed. In any case the discrepancy is in the direction which, if corrected for, would reduce our measured flux from Mars and lower the surface temperature. The correlations between Γ, ΔT_{AS}, and z make uncertainties in these quantities difficult to estimate, but the errors are considerably smaller than the range allowed from model to model. For example, the standard deviation of z in Model 3 for the P(16) line is about 0.004 if Γ and ΔT_{AS} are kept fixed.

Previous data[2] can be compared with the parameters we have fitted to our data. The effective continuum temperature near the $^{13}CO_2$ lines is about 250 K (Fig. 3). Mariner 9 (ref. 7), looking at the sub-solar point as we did, obtained a temperature near 11 μm of about 260 K. Mariner 9 also measured a temperature lapse rate of 2.5 K km^{-1} and an atmospheric temperature at the surface about 25 K cooler than the surface itself. These values are close to those used in Model 2 (Table 1). The parameter z is of particular interest because our data indicate a higher value than expected in all models. Some limits can be placed on the ranges of the three factors comprising z. Mariner 9 reported a surface pressure of 6 mbar with a range from 4 to 8 mbar because of terrain changes. Our results place an upper limit of 12 mbar because at this pressure the effects of collisional line broadening would have become apparent. A value of 0.24 s^{-1} was taken for the Einstein A coefficient of $^{12}CO_2$ (refs 8,9). The correct value for $^{13}CO_2$ may, however, be somewhat different because this coefficient is strongly influenced by the Fermi resonance between the lower level of the absorbing transition and the 02^00 vibrational level. Even a small change in the mass of the carbon atom affects the strength of this interaction. Measurements of the relative output power of carbon dioxide lasers operating on the two isotopic species suggest that the ratio $A(13/12)$ is about 2/3 (C. Freed personal communication). Taking a value for surface pressure of 6 mbar, the terrestrial value of 0.011 for $R(13/12)$, and assuming a value of 2/3 for $A(13/12)$, gives a value of 0.007 for z, a number about three times smaller than those in Table 1 which fit our present measurements. The cause of this discrepancy is not clear.

Because $^{12}CO_2$ was expected to be 90 times more abundant than $^{13}CO_2$, we made the $^{12}CO_2$ measurements first. The results, however, were not as significant as those for $^{13}CO_2$. Because of the large width of the $^{12}CO_2$ line, measurements were made in bands 150 MHz wide distributed from 550 MHz below to 350 MHz above the expected frequency of the line centre. The bands could not be measured simultaneously because a suitably wide filter bank was not available. The measured flux was independent of frequency to within a standard deviation of 20%, indicating a line broader than the frequency range examined. The data are consistent with a continuum of 250 K folded into an absorption line with a flux of less than 2×10^{-23} W Hz^{-1}

(200 K) and an equivalent width greater than 670 MHz (0.022 cm^{-1}). A computer simulation using a lapse rate of 2.5 K km^{-1}, a value for ΔT_{AS} of 30 K, and a surface pressure of 6 mbar predicts an equivalent width of 400 MHz for the $^{12}CO_2$ line. The difficulties of accurate calibration mean that the discrepancy is probably not significant, although its direction is similar to that found for $^{13}CO_2$, corresponding to excess absorption.

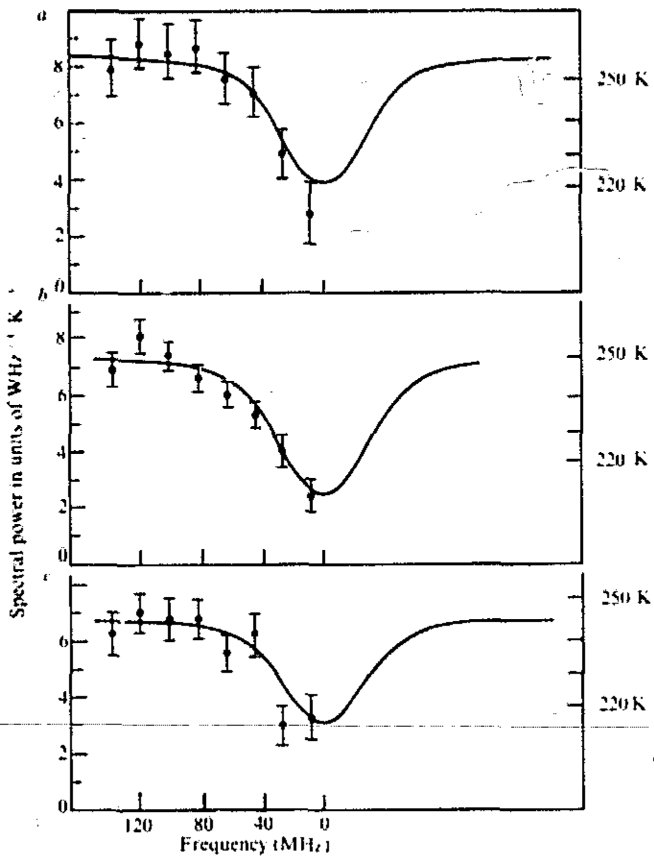

Fig. 3 Data obtained for the P(26) *a*, P(16) *b*, and P(22) *c*, rotational lines of $^{12}CO_2$. In *a*, T_s = 256 K, and equivalent width = 50 MHz; *b*, T_s = 250 K, and equivalent width = 66 MHz; *c*, T_s = 246 K, and equivalent width = 49 MHz. The original data has been unfolded and plotted in the format of Fig. 2*a* as half of an infrared line. The ordinate is received spectral power in W Hz^{-1} divided by Boltzman's constant *k* and referenced to the top of the Earth's atmosphere. Absolute temperatures for black bodies of equal spectral radiance are shown at the right of the figure. Error bars represent plus and minus one standard deviation and correspond closely to predictions of the theory of heterodyne mixing[10]. The abscissa MHz is measured from the expected position of line centre. The P(26) and P(22) lines each represent about 1 h of observation, the P(16) line about 2 h. The solid curves represent absorption line profiles calculated in a computer simulation of the Martian atmosphere (see text).

Table 1 Parameters for computer simulation

	Γ	ΔT_{AS}	z
Model 1	5 K km^{-1}	25 K	0.027
2	2.5 K km^{-1}	30 K	0.02
3	1.3 K km^{-1}	35 K	0.017
4	0 K km^{-1}	45 K	0.02

The results demonstrate that infrared heterodyne spectroscopy can be used in astronomy for spectral resolution exceeding by several orders of magnitude that obtained with conventional techniques, although the copper-doped germanium photomixer used had a sensitivity about 25 times less than the theoretical limit of 2×10^{-20} W Hz^{-1} for heterodyne detectors at 11 μm. Continuously tunable infrared lasers would allow high resolution of lines anywhere in the infrared band and perhaps the detection of absorption lines of interstellar gas against bright sources.

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A 10μm HETERODYNE STELLAR INTERFEROMETER*

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Received ______________________

ABSTRACT

A spatial interferometer for 10μm wavelengths which uses two independent telescopes separated by 5.5 meters, heterodyne detection of the infrared radiation, and path equalization by a variable length r.f. cable, has given interference fringes from radiation of the planet Mercury. Continuous fringe observations during 4000 sec. indicate remarkable stability in the optical path difference through the atmosphere and two telescopes, fluctuations between 20 sec averages being about 1/6 of the 10μm wavelength.

Analytic Subject Index - 61.4

†NSF Fellow 1966-1972

A 10μm HETERODYNE STELLAR INTERFEROMETER

A two element spatial interferometer, operating with two 10μm wavelength heterodyne receivers on a baseline of 5.5 meters, has been constructed and successfully tested on an astronomical source. In purpose, the apparatus is similar to Michelson's stellar interferometer in that it provides very high angular resolution of infrared stars and other localized sources; in construction, however, the instrument more closely resembles a long-baseline microwave interferometer.[1,2]

Presently, the interferometer uses the two independent solar auxiliaries of the McMath Solar Telescope at Kitt Peak National Observatory.[3] Each auxiliary telescope consists of a flat heliostat of about 0.4m^2 collecting area followed by a fixed off-axis focusing mirror and subsequent optical flats which direct the beam to a fixed focus at a receiver. The total optical path within each telescope is about 120 meters. The steerable flats of these two separate telescopes are situated on an east-west baseline with a center to center separation of 5.5 meters. An interferometer of this type can resolve angles as small as about $\lambda/2D$, where λ represents the wavelength of the received radiation, and D the separation between the receiving apertures. There are many astronomical sources of intense 10μ radiation which have not been resolved and which are thought to have angular dimensions between 1 and .01 arc sec, requiring baselines between 1 and 100 meters to be resolved. Some of these objects have essentially no visible radiation; others are visible stars with

circumstellar dust clouds of unknown size and shape which emit the dominant part of the 10μm radiation.

At each focus of the two separate telescopes, a high speed Ge:Cu photoconductor mixes the stellar radiation with a local oscillator beam from a stable 1 watt CO_2 laser[4] as indicated in Figure 1. The radio frequency beat signals from each photomixer preserve the original phase and amplitude characteristics of the infrared radiation. The photomixer outputs are each amplified and passed through a stepped coaxial cable delay line which compensates for the changes in optical path length produced as the infrared source is tracked across the sky. For interference of two beams over a frequency bandwidth $\Delta\nu$, the path length must be equalized to a distance small compared with $c/\Delta\nu$ to avoid any significant correlation loss. Hence, the 1200 MHz bandwidth of these signals requires that the delay cable be maintained accurate to a few centimeters. In a direct detection interferometer, such as Michelson's original instrument, the relatively large signal bandwidth enhances sensitivity but requires accuracy of optical path lengths comparable with the wavelength of light involved, which is considerably more demanding than the delay cable accuracy required for an inherently narrow-band heterodyne interferometer.

Following the rf delay line is a broadband correlator which multiplies together the two appropriately delayed photomixer signals. The correlator output signal represents the fringe amplitude; it is proportional to the degree of coherence between wavefronts arriving from the source at

the two receivers and, for a given flux, approaches zero for a source which is resolved. The frequency of this signal depends on the motion of the source through the interferometer fringe lobes and on the frequency difference between the two laser local oscillators. In order to produce a fringe signal convenient for processing and to avoid undersirable interaction between the lasers, the local oscillators are phase-locked with a 5 MHz frequency difference. This 5 MHz frequency is later removed from the correlator output signal in a single sideband demodulator, yielding the natural fringe signal. For a horizontal east-west baseline the natural fringe frequency is given by $\frac{\Omega D \cos\delta \cos H}{\lambda}$ where Ω is the earth's rotation rate, δ is the source declination, and H is the source hour angle, which increases linearly with time.

The planet Mercury was the strongest convenient source on which to test the interferometer. Its diameter at the time of measurement was six arc seconds, or about ten times the fringe lobe spacing, and hence its disk was resolved. However, Mercury was at maximum elongation from the sun, so that its temperature distribution was strongly peaked toward the sub-solar edge of the planet. The resultant fringe modulation signal was comparable with the level expected from the strongest 10μm "infrared star", IRC+10216, and 5 to 10 times greater than that expected from the red giant star Betelgeuse. Mercury was observed in late July and early August, 1974, after

sunrise between 15° and 45° above the eastern horizon, yielding natural fringe frequencies between 4 and 20 Hz.

Information about fluctuations in the relative phase of infrared signals arriving at the two telescopes was of primary interest in these initial tests. Such fluctuations, caused largely by the atmosphere, are expected to be the limiting factor for stellar interferometers operating at visible and infrared wavelengths. The correlation signal from Mercury was expected to be centered in frequency at the theoretical value predicted from the parameters of the planet's motion and of the interferometer baseline, but broadened in frequency by atmospheric phase fluctuations. Therefore, a power spectrum centered at the predicted frequency was computed from recorded data taken during 4000 seconds of continuous observation. Figure 2 shows a composite spectrum with a resolution of $\frac{1}{4000}$ Hz at the center--the smallest frequency interval justified by the length of observation. In the wings of the line, a resolution of $\frac{1}{800}$ Hz is used. It is seen from this figure that a substantial fraction of the signal energy falls within an exceedingly narrow spectral width, and that some signal is spread over a much wider spectral region. The central peak, while very narrow, was displaced about $\frac{1}{40}$ Hz from the calculated value, presumably due to some imprecision in determination of the required parameters. In the wings of this signal, the power spectrum is approximately proportional to $(\nu-\nu_o)^{-2/3}$, where $\nu-\nu_o$ is the deviation from the central

peak, and is noticeably above noise as far as about $\frac{1}{10}$ Hz from the central peak.

The unexpectedly long-term coherence of the signal made evident by Figure 2 suggested a direct computation of the phase difference between the correlation signal and the predicted interference fringe frequency. Figure 3 shows successive 20-second averages of this difference, which exhibits little tendency to wander from a constant and has a root mean square deviation of only 60 degrees. Previous tests with the same fringe detecting apparatus of the propagation fluctuations within the solar telescope building showed them to be comparable with those seen in the signal from Mercury. Hence even the small phase variations observed may be associated largely with fluctuations of the two separate 120 meter optical paths within the telescope structure, or with imperfect tracking of the telescopes on Mercury, rather than with essential atmospheric effects. These phase fluctuations within the telescope system can be compensated in later versions of the instrument by reference laser beams.

The high degree of coherence indicated by Figure 2 was obtained on one morning out of about 6 periods of observations when the "seeing" was relatively good (angular fluctuations $\approx$ 1 arc second). Other observations frequently showed the fluctuations to be much larger in both amplitude and rate of change, but these have not yet been analyzed in detail. The greater part of the observation was made with

Mercury low on the horizon, for which the projected separation between telescopes was about 2 meters, and the planet was viewed through approximately 3 times greater depth of atmosphere than would occur at the zenith.

While the signal-to-noise was quite adequate for this initial test, further improvement is important for the wide variety of astronomical measurements which can be envisaged. Atmospheric seeing is sufficiently good that larger telescope apertures may be used to increase the signal strength by about one order of magnitude. The system noise for heterodyne detection has a theoretical minimum value proportional to $h\nu$ per unit bandwidth for a photon frequency ν.[5] The Cu-doped germanium detectors used had a noise level about 25 times larger than this limit, but other detectors (Hg Cd Te photodiodes in particular) have been demonstrated with noise as small as $4\ h\nu$, and hence improvement by a factor of 6 appears practical. The integration time can of course be longer than the 68 minutes used here; less well-known is how stable the relative phase differences through the atmosphere may be under the best of seeing conditions or with greater distances between telescopes. Less stability would decrease the effective signal-to-noise ratio obtainable for a given system. Under good seeing conditions infrared stellar images can be smaller than what appeared to be the case during this observation. It is thus reasonable to expect

coherence times even longer than the 4000 seconds obtained in this experiment, and that a still larger fraction of the signal energy can be within a very narrow spectral width. However, any firm evaluation of fluctuations under other conditions must await further measurement.

Atmospheric stability, while still incompletely known, seems adequate to allow extensive interferometry on astronomical objects at infrared wavelengths comparable with or longer than 10μm, and a wide variety of infrared spatial interferometers may be envisaged. Longer baselines of variable length and orientation are needed; it is for such use that heterodyne detection and path length equalization by rf cable is especially convenient. The present two-element system can measure sizes of some of the brighter localized infrared sources, and improvements noted above should allow examination of the brightness distributions of a large number of infrared astronomical objects under very high angular resolution. In addition, the r.m.s. phase fluctuation of 60° found for each of about 200 determinations during the present observation suggests that the position of Mercury was determinable from this experiment with a precision of about 0.01 arc sec. This gives some promise that measurements of fringe phase will allow highly accurate determinations of stellar positions or of the earth's rotation.

FIGURE CAPTIONS

Figure 1: Schematic diagram of infrared heterodyne interferometer. Separation of telescopes is 5.5 meters.

Figure 2: Power spectrum of correlation signal. The root mean square system noise in 1/4000 Hz is approximately 3 units. Most of the fluctuations in the above data are attributed to signal variation due to atmospheric instability.

Figure 3: Phase deviation from predicted frequency. A linear slope corresponding to 1/40 Hz has been removed. Points for which power at the predicted frequency dropped below 15% of the mean are not plotted. In the absence of atmospheric fluctuations, system noise would be expected to produce approximately a 30 degree root mean square deviation.

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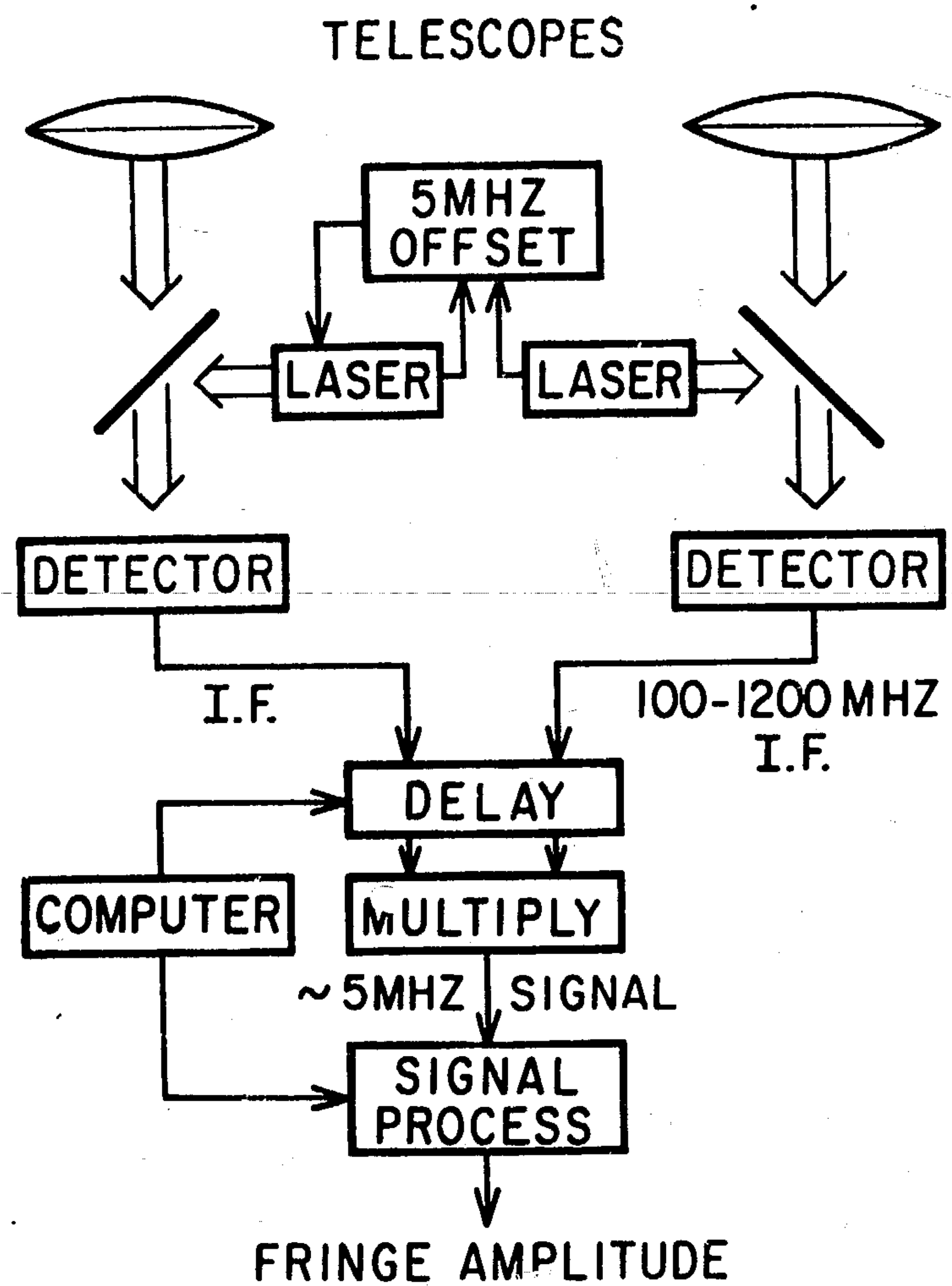
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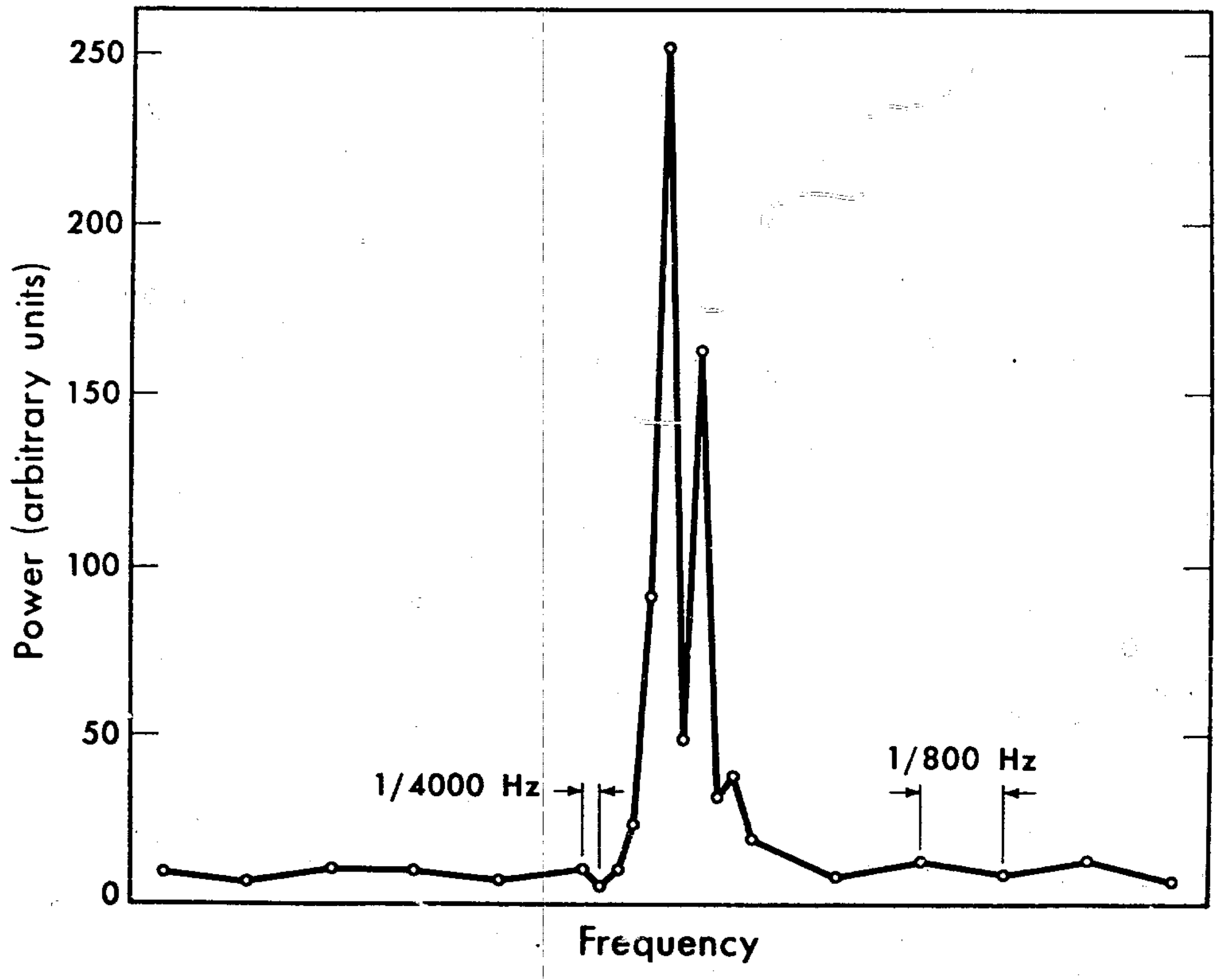

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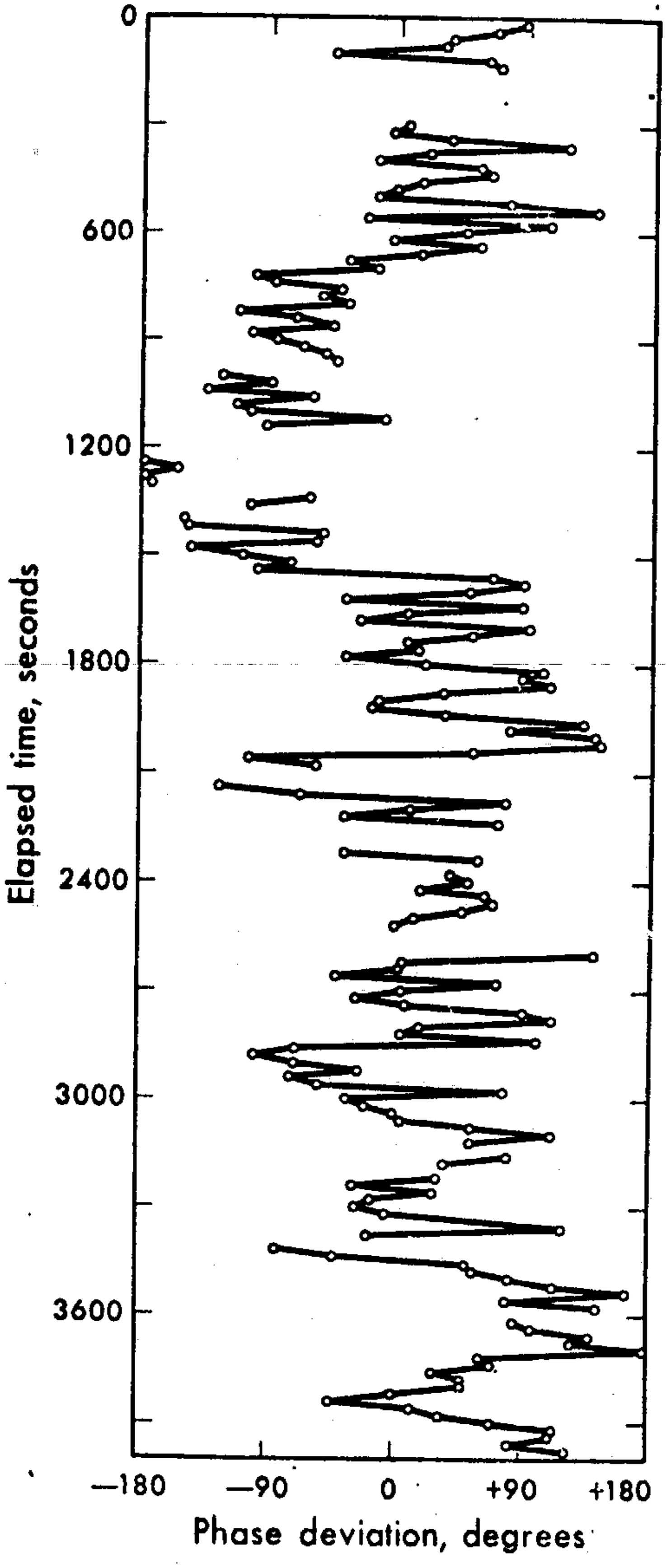
1/4000 Hz
1/800 Hz
Frequency



0
600
1200
1800
2400
3000
3600
Elapsed time, seconds
−180
−90
0
+90
+180
Phase deviation, degrees

COPY

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ABSTRACT

WL2. An Infrared Stellar Interferometer Using Heterodyne Detection. Michael A. Johnson, Department of Physics, University of California, Le Conte Hall, Berkeley, Calif. 94720. -- A two-element stellar interferometer, operating with 10-μm wavelength heterodyne receivers, has been constructed. Each receiver, located at the fixed focus of a reflecting telescope, uses a stabilized carbon dioxide laser as a local oscillator and a photoconductor as a mixing element. We have achieved nearly quantum-noise-limited performance over a bandwidth exceeding 1 GHz with these detectors. Mounted on two 75-cm telescopes whose outputs can be efficiently matched to the local oscillators, this system will be able to detect many of the bright infrared sources. Correlation of the receiver outputs, made after suitable delay has been introduced, is followed by signal processing designed to efficiently determine fringe amplitude. For example, the interferometer may be operated simultaneously in both an intensity-correlation mode and the normal amplitude-correlation mode to allow for some phase instability due to atmospheric conditions. Initial tests will be carried out on a baseline of 5 m with an angular resolution of 0.2 arc s. Extension of this baseline to more than 100 m, using both existing fixed telescopes and newly designed moveable telescopes, will be discussed. Comparisons of this instrument to the classical Michelson stellar interferometers and to long baseline radio wavelength systems will be made.

AMERICAN ASTRONOMICAL SOCIETY

Abstract Submitted for the 26-29 March 1974 meeting COPY

Category: Instruments and Techniques Date Submitted

Read by: D. W. Peterson

Heterodyne Spectroscopy of CO_2 on Mars.* D. W. Peterson, M. A. Johnson, UC Berkeley - An eight-channel heterodyne receiver operating near 11μm was used to measure line profiles of $C^{13}O_2^{16}$ in the Martian atmosphere. The receiver used copper dopped germanium as the photomixer and a carbon dioxide laser as the local oscillator. Each channel was 18 MHz wide, giving a resolving power of 1.5×10^6 at 11μm. Profiles were determined for the P(16), P(22), and P(26) lines of the 00^01-10^00 vibration-rotation band of $C^{13}O_2^{16}$. The equivalent widths of each of these lines was approximately 45 MHz (.0015 cm^{-1}). The amount of radiation detected at line center was 40% of that detected in the continuum. Simple atmospheric models were calculated for Mars and the above measured values are consistent with a terrestrial C^{13}/C^{12} abundance and the temperature structure of Mars' atmosphere measured by Mariner 9. A measurement of the P(20) line of $C^{12}O_2^{16}$ at 10.6um showed no observable line shape. This allows us to place a lower limit of 600 MHz (.02 cm^{-1}) on the equivalent width of this line.

*Work partially supported by NASA Grants NGL 05-003-272 and NGR 05-003-452

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Abstract submitted for the Gainesville meeting

Category Instruments and techniques Date submitted October 8, 1974

Read by M. A. Johnson

Results From the 5.5 Meter Infrared Stellar Interferometer. M. A. Johnson, A. L. Betz, C. H. Townes, U. C. Berkeley. A two element stellar interferometer, operating with 10 μm wavelength heterodyne receivers on a baseline of 5.5 meters and having an angular resolution of 0.2 arc seconds has been successfully tested on an astronomical source. Presently, the interferometer uses the two independent solar auxiliaries (0.4 square meters area) of the McMath Solar telescope at Kitt Peak National Observatory. Information about atmospheric fluctuations, causing variation in the relative phase of infrared signals arriving at two separate telescopes, was of primary interest in these initial tests. Such fluctuations are expected to be the limiting factor for stellar interferometers operating at visible and infrared wavelengths. The planet Mercury at maximum western elongation from the sun was the strongest convenient source for this test. Motion of the planet through the lobes of the interferometer produced a quasi-sinusoidal correlation signal whose amplitude and phase were modulated by the atmospheric fluctuations. A power spectrum centered at the theoretically predicted frequency was computed for data from 4000 seconds of continuous observation. The spectrum had a sharp central spike unresolved at 1/4000Hz resolution, a power approximately proportional to $(\Delta\nu)^{-2/3}$, where $\Delta\nu$ is the deviation from the central peak, and remained noticeably above noise as far as 0.1 Hz from center. Two hundred successive 20 second averages of the phase difference between the signal and the predicted fringe frequency showed little tendency to wander from a constant and had a root mean square deviation of 60 degrees. These preliminary results suggest that the atmosphere has a "phase memory" which may permit high resolution maps and accurate position measurements to be made in the infrared. Work partially supported by NASA Grants NGR 05-003-402 and NGL 05-003-272.

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